Dynamical Climatology

Climatic impact of Amazon deforestation.

by

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In a 3-year GCM simulation, replacing Amazon tropical forest and savannah with pasture, the local climatic response was dominated by a weakened hydrological cycle, with less precipitation and evaporation, and an increase in surface temperature. The relative impact on the local climate due to changes to individual vegetation parameters was investigated. The combined changes to roughness and albedo were largely responsible for the reductions in precipitation and evaporation in the deforestation simulation. Decreased roughness dominated the reduction in evaporation and also the increase in temperature, while the change in the moisture flux convergence (measured as precipitation - evaporation), was largely a result of the increase in albedo.

The Amazon basin contains about half of the world's tropical forest (Dickinson 1987). Population pressure and subsequent demands for crop production, timber and fuelwood have led to rapid deforestation. Quantitative estimates of the rate of deforestation from analysis of LANDSAT satellite observations indicate that rates are increasing exponentially in many regions (Fearnside 1987, Malingreau and Tucker 1988); however there is much dispute over the precise figures due to the varied interpretation of such data (Neto 1989). Removal of the protection afforded by natural cover can lead to soil erosion which is particularly detrimental to tropical soils as nutrients and humic reserves are concentrated in the topmost layers; the ecosystem is disturbed and species diversity may be threatened (Lavelle 1987).

Deforestation has important implications for the climate system as energy and water fluxes between the surface and atmosphere are closely linked to the nature of the land surface. Within the Amazon basin, it is estimated that 50% of the local rainfall is derived from local evaporation (Salati et al, 1978). It has been suggested that a significant reduction in tropical forest might reduce evaporation and consequently reduce rainfall, making re-establishment of dense forest more difficult (Salati 1987). Recently various studies concerning the impact of surface changes on climate have been carried out using three-dimensional Atmospheric General Circulation Models (AGCMs). A review of tropical deforestation experiments (Henderson-Sellers 1987) shows that substantial differences exist between the schemes for representing physical processes (parametrizations) and between methods employed to simulate land transformations in AGCMs. As a result AGCMs have not presented a uniform picture of the potential effects of deforestation on climate. This has been due in part to the use of rather simple land surface schemes and the lack of grid scale data with which to calibrate the models. However, some common points have emerged from these simulations. Firstly, albedo, roughness and hydrology are the most important components in land transformation. Secondly, results are sensitive to the parametrizations in the model, to the choice of input land surface data, and the climatology of the AGCM used. Over the past few years more realistic land surface parametrizations have been included in various AGCMs including that of the Meteorological Office. The studies referred to above have shown that such developments are critical to modelling deforestation.

This paper describes experiments which were carried out using the $2\frac{1}{2}^\circ$ x $3\frac{3}{4}^\circ$ resolution AGCM described in Slingo et al (1989), but including a more complex representation of interactive cloud processes (Smith 1989). To reduce computational time, radiative processes were computed interactively every 3 model hours. The land surface parametrization (Warrilow et al, 1986) includes a 4-layer soil temperature scheme. Interception of precipitation by a vegetation canopy is represented so allowing zero resistance to re-evaporation and potentially a more realistic partitioning of energy between latent and sensible heat fluxes. The hydrological scheme diagnoses surface runoff from excess of rainfall over infiltration capacity (taking into account the spatial variability of rainfall statistically), and sub-surface runoff from the gravitational drainage of soil moisture (Warrilow 1986). Geographical variation of land surface and soil types is based on the work of Wilson and Henderson-Sellers (1985). Their original 1° x 1° resolution primary and secondary vegetation and soil datasets were used to create spatially varying datasets of 17 soil and vegetation parameters which were interpolated onto the $2\frac{1}{2}^\circ$ x $3\frac{3}{4}^\circ$ model grid (Warrilow and Buckley 1989).

Control and deforestation experiments were run for 3 years starting at the end of June. In the deforestation experiment all grid boxes which were defined as either tropical forest or savannah on the 1° x 1° grid were replaced by tropical pasture north of 30° S over South America (figure 1). Soil characteristics, except surface infiltration capacity, were left unaltered. Results are given for the southern part of Amazonia (shaded area in figure 1) where the largest change in land

surface characteristics occurred. Table 1 lists the average vegetation parameters for this region for the control and deforested simulations . Root depth is the average depth of soil from which moisture is available to plant roots. The albedo of the region (0.14) is higher than that assumed for tropical forest (0.12) due to the proportion of the region encompassing savannah. Surface resistance for vegetation is an average value of stomatal resistance for conditions of freely available soil moisture. The infiltration factor accounts for the way in which vegetation modifies the surface infiltration capacity of bare soil.

It is instructive to first assess the performance of the control simulation compared with observational data. The seasonal movement of the ITCZ dominates the climate of the Amazon basin. During the Southern Hemisphere summer the area of maximum precipitation extends from 0° to 15°S and moves progressively northwards as the year proceeds (Salati 1987). Figure 2 illustrates that the model simulates the spatial distribution of rainfall well for both the Southern Hemisphere winter and summer. However, the magnitude of the rainfall for the region under consideration is slightly underestimated for the winter and overestimated for the summer. Comparison with observations in Table 2 shows that the annual simulation of the hydrology by the model is quite good and also that the surface temperature agrees well. It should be noted that it is extremely difficult to obtain accurate estimates of such quantities because observations are too sparse to provide grid scale means. Runoff is only quoted for a particular basin and in this case takes account of a different set of tributaries to that defined by

this region. Evaporation is based on only a few direct observations and empirical calculations.

Comparison of surface quantities for a single model grid square with that of Shuttleworth's (1988) data at a site in central Amazonia indicates that modelled total evaporation differs by 15% from the observed, and that modelled canopy evaporation is 71% compared with the observed 25% of total evaporation. Overestimation of canopy evaporation is probably present in other land surface schemes and Shuttleworth and Dickinson (1989) suggest that this could be due to the extension of a single point description of the rainfall interception process to the grid scale area in a region where convective rainfall events dominate. Hence, the areal distribution of rainfall intensity may need to be incorporated into this aspect of land surface schemes.

The impact of deforestation on local climate was investigated by comparing the deforested and control simulations. Table 3 summarises the results for a variety of surface variables for each experiment. The hydrological cycle was significantly weakened by deforestation, with a reduction in evaporation, rainfall and runoff. Surface runoff is less as the reduction in intensity and frequency of rainfall events predominates over the opposite tendancy due to the reduction in infiltration capacity. The decrease in available soil moisture occurs as a result of the marked reduction in root depth. Pasture reflects more solar radiation than forests which are very efficient absorbers and scatterers of short-wave radiation. Consequently the net energy absorbed by the surface was diminished. By itself a reduction in net

downward surface radiation would imply a temperature decrease but this is offset by a reduction in evaporative cooling leading to an overall rise in temperature. The decrease in the latent heat flux was primarily responsible for a marked increase in the Bowen ratio (defined as the ratio of sensible to latent heat).

Figure 3 depicts the seasonal variation of precipitation, evaporation and temperature for the control, the deforested and the difference between the two simulations. The pattern of the decrease in precipitation is consistent but fairly noisy throughout the year. Evaporation is also less throughout the seasonal cycle with the maximum differences occuring in the winter and spring when evaporation is controlled by the limited availability of soil moisture. Comparison of figure 3(d) with 3(f), shows that temperature is strongly influenced by changes in evaporation despite the reduction in albedo.

Although the total precipitation has decreased it is important to note that there are for example local increases over some parts of the Andes which are statistically significant at the 90% confidence level.

In order to gain a better understanding of the physical mechanisms operating, two eight-month simulations, using the same initial data as the control and deforested experiments were carried out to investigate the relative impact due to changes to albedo and roughness alone. Table 4 summarises the differences from the control simulation of some of the surface variables for the increased albedo, decreased roughness, and total deforestation experiments. Precipitation within the Amazon

basin originates from two sources, first from the recycling of water vapour released during evapotranspiration, and second from the moisture flux convergence into this area. The decrease in moisture flux convergence (measured as precipitation - evaporation) is due mainly to increased albedo although there is some contribution from the change in roughness. Increased albedo reduces the heat source, weakening ascent and boundary layer convergence (Charney et al, 1977). Reduced roughness can also decrease the moisture flux convergence as it weakens the convergence (associated with frictional drag near the surface) into the continental surface low (Sud et al, 1988). Decreased roughness dominates the reduction in evaporation and the associated temperature increase. The forest canopy is wet for most of the year (implying low surface resistance) and so a decrease in evaporation is to be expected as roughness decreases (Rowntree 1988). Increased albedo reduces the available energy for upward turbulent transfer of latent energy. Hence, changes in both albedo and roughness contribute to the overall decreases in precipitation and evaporation seen in the deforestation simulation.

The results of these experiments provide a much clearer indication of the impact of deforestation on the local climate compared with previous GCM experiments. However it must be borne in mind that these results are highly sensitive to the formulations employed within our model and our ability to make firm predictions based on these results is inhibited by the lack of observed data for forested and deforested areas with which to verify these schemes. Hence, it is considered premature to make a detailed assessment of remote effects at present.

The inclusion of a canopy and an improved hydrology scheme is important and our results can be compared with a similar study carried out by Dickinson and Henderson-Sellers (1988) (referred to as DHS from now on). They incorporated a land-surface scheme with a canopy in the National Center for Atmospheric Research Community Climate Model which has a grid resolution of 4.5° x 7.5°. Their simulation assumed that all of the Amazon tropical forest in South America was replaced by impoverished grassland. Both experiments show a decrease in evaporation and increase in surface temperature (0.5 - 4.0°C in the DHS study compared with 0.5 - 5.0°C) . However DHS found no detectable change in rainfall compared with the consistent decrease (average 1.3mmd^{-1} (20%)) shown here.

The improvements to the representation of the land surface in the AGCM outlined in this paper are part of a continual process of the development and assessment of more physically-based land surface representations. In the future, more ground-based measurements together with satellite-derived global datasets of surface vegetation types could aid in this development, both as input to the model and to validate and adjust the land surface parametrizations (ISLSCP 1987). It is envisaged that with increased confidence in the modelling of physical processes a better assessment of the local, regional and global implications of deforestation can be made.

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Table 1: Vegetation parameters for the Control (C) and Deforested (D) Simulations

Vegetation Parameter	C	D
Rootdepth (cm)	127.4	61.9
Albedo	0.136	0.188
Surface Resistance (sm^{-1})	119.7	82.2
Roughness (m)	0.79	0.04
Canopy Capacity (cm)	0.22	0.14
Vegetation Fraction	0.93	0.84
Infiltration Factor	5.00	1.93

Table 2: Comparison of Surface Variables for the Control (C) Averaged over 3 Years with Observations (O)

Surface Variable	C	O
Evaporation (mmd^{-1})	3.1 (-6.6%)	3.34 (Willmott et al 1985)
Precipitation (mmd^{-1})	6.6 (+16.8%)	5.26 (Jaeger 1976)
Runoff (mmd^{-1})	3.40 (+23.0%)	2.76 (UNESCO 1971)
Temperature (°C)	23.55 (-0.5°C)	24.01 (Schutz and Gates 1971-1974)

Table 3: Summary of Surface Variables for Control (C) and Deforested (D) Simulations Averaged over 3 Years

Surface Variable	C	D	
Evaporation (mmd^{-1})	3.12	2.27	(-27.2%)
Precipitation (mmd^{-1})	6.60	5.26	(-20.3%)
Soil Moisture (cm)	16.13	6.66	(-58.7%)
Runoff (mmd^{-1})	3.40	3.00	(-11.9%)
Net Radiation (Wm^{-2})	147.29	125.96	(-14.5%)
Temperature (°C)	23.55	25.98	(+10.3%)
Sensible Heat (wm^{-2})	57.19	60.15	(+5.2%)
Bowen Ratio	0.85	1.50	(+76.5%)

Table 4: Summary of the Differences in Surface Variables for Increased Albedo (A), Decreased Roughness (R) and Deforested (D) from Control (C) Simulation Averaged over 8 months.

Surface Quantity	A-C	R-C	D-C
Evaporation (E) (mmd^{-1})	-0.20	-0.43	-0.61
Precipitation (P) (mmd^{-1})	-0.75	-0.69	-1.34
P-E (mmd^{-1})	-0.55	-0.26	-0.73
Temperature (°C)	-0.10	+2.24	+1.98

Figure Captions

Figure 1 All grid points which were defined as either tropical forest or savannah on the 1° x 1° grid were changed to tropical pasture north of 30° S over South America. The parameter values associated with these types are then interpolated onto the $2\frac{1}{2}°$ x $3\frac{3}{4}°$ grid. The shaded section shows the area used for averaging purposes for all results quoted and signifies the largest change in land surface characteristics in the southern region. Primary and secondary vegetation datasets were specified. For the region under consideration 42% forest and 17% savannah were changed to pasture for the primary dataset and 36% forest and 23% savannah were changed to pasture for the secondary dataset.

Figure 2(a) Observed precipitation pattern over South America (Jaeger 1976) for the Southern Hemisphere winter (June, July and August). Contours are at 0.1, 1.0, 2.0, 5.0, 10.0, 20 mmd^{-1} and shading is above $5mmd^{-1}$.

Figure 2(b) Simulated precipitation pattern of the control experiment over South America for the Southern Hemisphere winter (June, July and August) averaged over 3 years. Contours are at 0.1, 1.0, 2.0, 5.0, 10.0, 20 mmd^{-1} and shading is above $5mmd^{-1}$.

Figure 2(c) As for 2(a) but for the Southern Hemisphere summer (December, January and February).

Figure 2(d) As for 2(b) but for the Southern Hemisphere summer.

Figure 3(a) Simulated monthly mean precipitation amounts (mmd^{-1}) averaged over the region under consideration. Broken line represents the control simulation (C) and the solid line the deforested simulation (D)

Figure 3(b) Simulated monthly mean difference (D - C) of precipitation amounts (mmd^{-1}) averaged over the region under consideration. Broken line represents the mean difference in precipitation.

Figure 3(c) Simulated monthly mean evaporation amounts (mmd^{-1}) averaged over the region under consideration. Broken line represents the control simulation (C) and the solid line the deforested simulation (D)

Figure 3(d) Simulated monthly mean difference (D - C) of evaporation amounts (mmd^{-1}) averaged over the region under consideration. Broken line represents the mean difference in evaporation.

Figure 3(e) Simulated monthly mean temperature (°C) averaged over the region under consideration. Broken line represents the control simulation (C) and the solid line the deforested simulation (D)

Figure 3(f) Simulated monthly mean difference (D - C) of temperature (°C) averaged over the region under consideration. Broken line represents the mean difference in temperature.

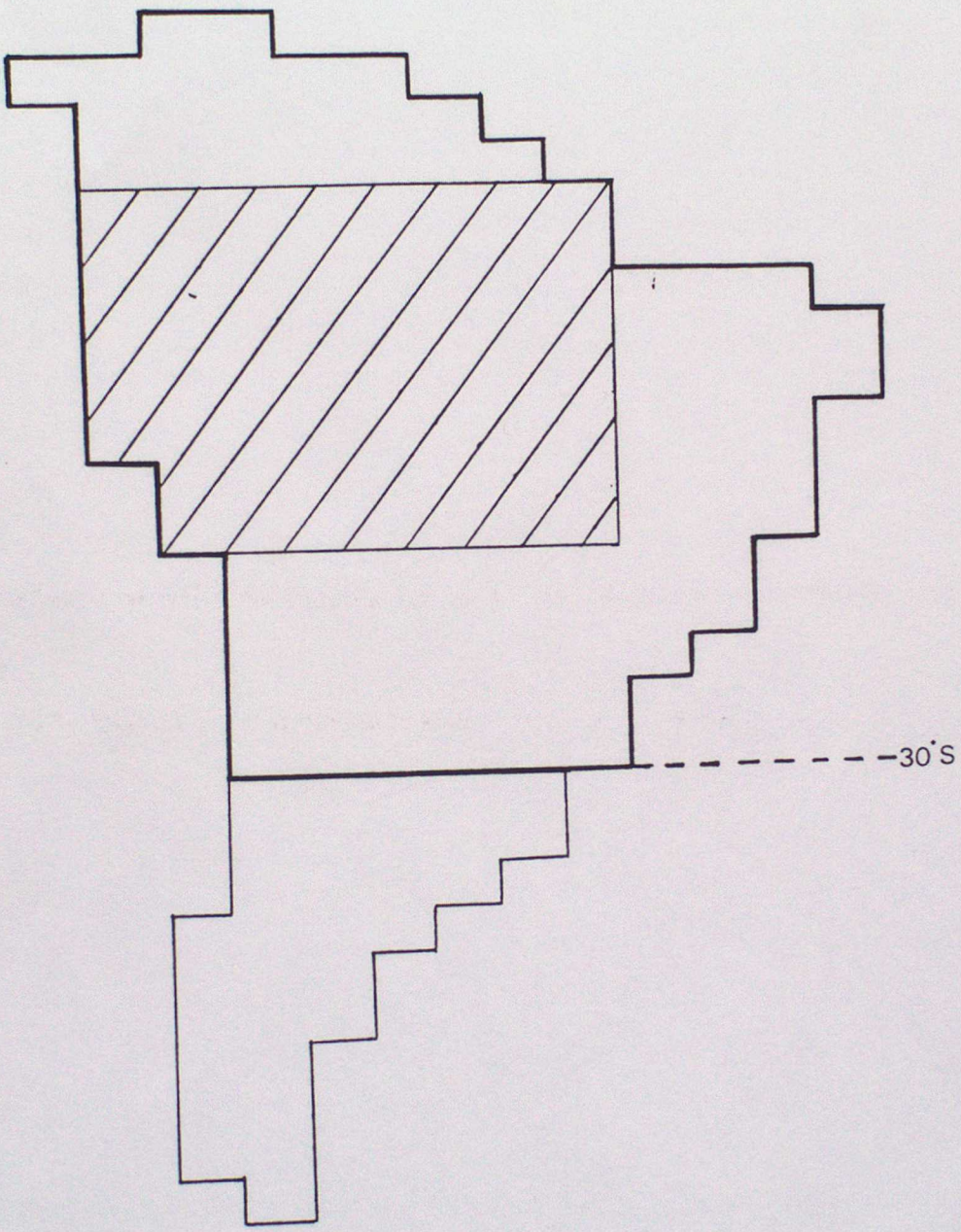

FIGURE 1

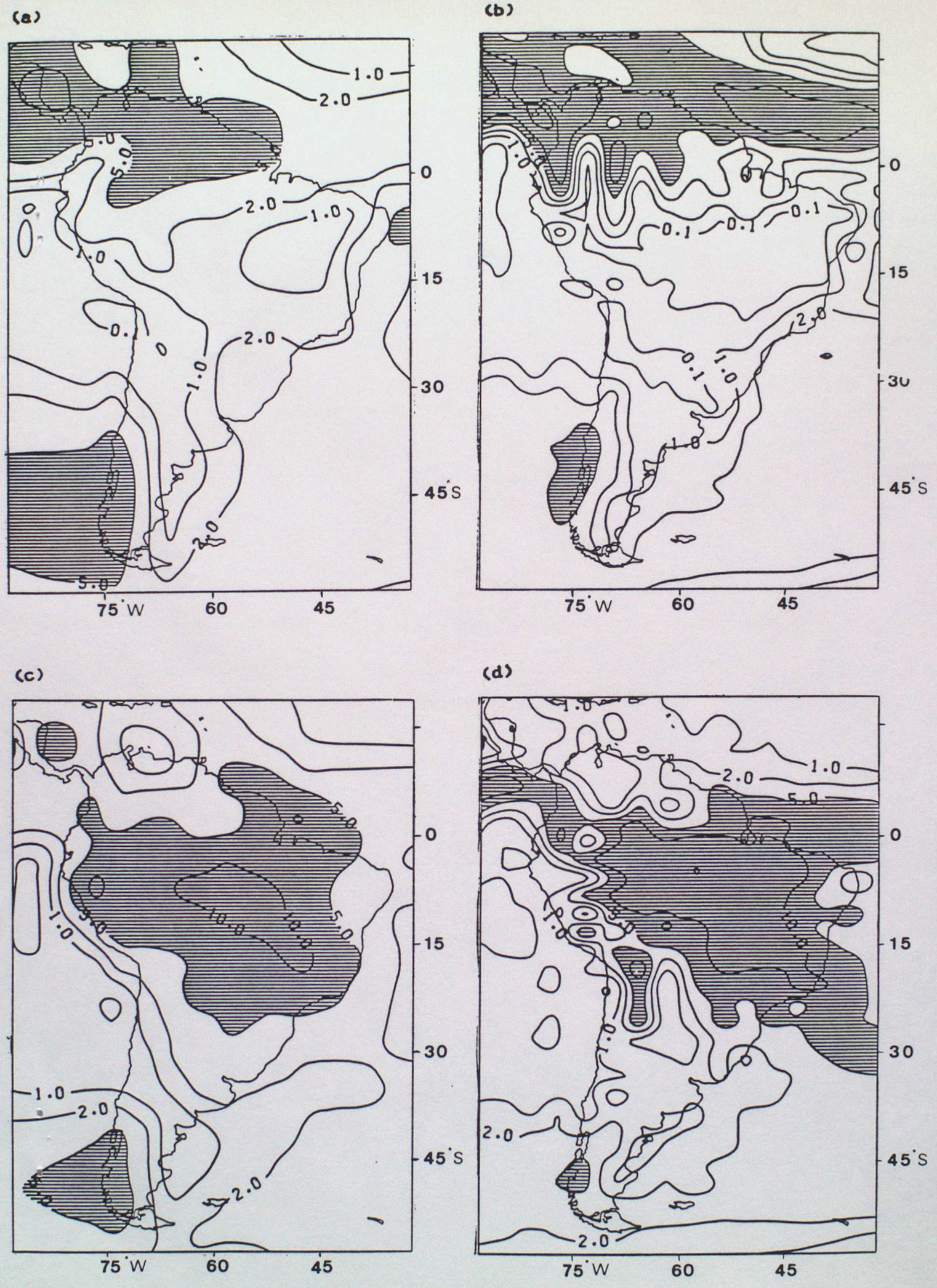

FIGURE 2

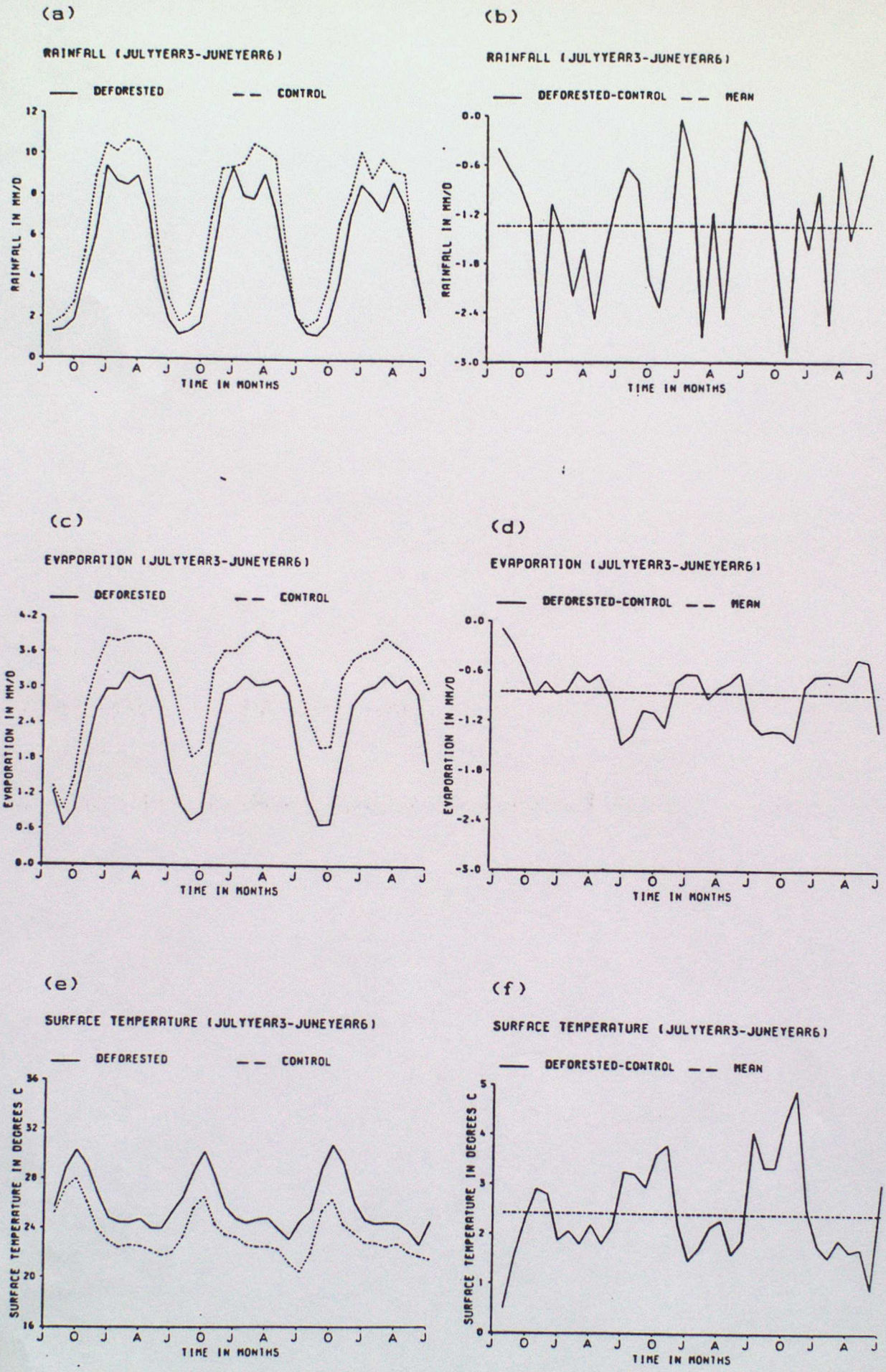
(a)
RAINFALL (JULYYEAR3-JUNEYEAR6)
DEFORESTED
CONTROL
RAINFALL IN MM/D
TIME IN MONTHS
(b)
RAINFALL (JULYYEAR3-JUNEYEAR6)
DEFORESTED-CONTROL
MEAN
RAINFALL IN MM/D
TIME IN MONTHS
(c)
EVAPORATION (JULYYEAR3-JUNEYEAR6)
DEFORESTED
CONTROL
EVAPORATION IN MM/D
TIME IN MONTHS
(d)
EVAPORATION (JULYYEAR3-JUNEYEAR6)
DEFORESTED-CONTROL
MEAN
EVAPORATION IN MM/D
TIME IN MONTHS
(e)
SURFACE TEMPERATURE (JULYYEAR3-JUNEYEAR6)
DEFORESTED
CONTROL
SURFACE TEMPERATURE IN DEGREES C
TIME IN MONTHS
(f)
SURFACE TEMPERATURE (JULYYEAR3-JUNEYEAR6)
DEFORESTED-CONTROL
MEAN
SURFACE TEMPERATURE IN DEGREES C
TIME IN MONTHS

FIGURE 3

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